Control of the interaction in a Fermi-Bose mixture

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We control the interspecies interaction in a two-species atomic quantum mixture by tuning the magnetic field at a Feshbach resonance. The mixture is composed by fermionic ^{40}K and bosonic ^{87}Rb. We observe effects of the large attractive and repulsive interaction energy across the resonance, such as collapse or a reduced spatial overlap of the mixture, and we accurately locate the resonance position and width. Understanding and controlling instabilities in this mixture opens the way to a variety of applications, including formation of heteronuclear molecular quantum gases.

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Interactions between particles affect profoundly the energy spectrum of ultracold quantum gases and determine most of their properties, including superfluidity. Many different physical scenarios have been opened by magnetically tunable Feshbach resonances [1], which can be exploited to tune the interactions beyond their natural values. The availability of such resonances for most Bose and Fermi gases currently explored in experiments has allowed to study a series of fundamental phenomena, such as superfluidity in Fermi gases at the BEC-BCS crossover [2], formation of molecular quantum gases [3], or observation of Efimov states [4]. Heteronuclear mixtures and in particular mixtures of the two quantum statistics, i.e. Fermi-Bose systems, represent an even richer system, since more than one interaction between the constituent particles come into play. In particular, achieving a control of the interspecies interaction in these system is expected to give access to a large range of new phenomena. Notable examples are dipolar molecular gases [5], boson-induced fermionic superfluidity [6], novel quantum phases in strongly correlated systems [7]. Feshbach resonances have been so far studied in mixtures of ^{6}Li-^{23}Na [8], ^{40}K-^{87}Rb [9, 10, 11], ^{6}Li-^{7}Li [12], but no fine tuning of the interaction has been reported so far.

In this work we report a study of the properties of Fermi-Bose mixture at an interspecies Feshbach resonance, which we exploit to tune the fermion-boson scattering length a_{FB} within a large range of positive and negative values. We are able to drive the system into a regime where the interaction energy dominates the behavior, leading to the onset of instabilities [13]. In particular we observe a collapse of the system for large attractive interactions and the effects of a reduced spatial overlap of the components for large repulsive interactions. We study the boundaries between regions characterized by a_{FB} with opposite sign to precisely determine the resonance parameters that are necessary to realize a fine tuning of the interaction. Fast tuning of a_{FB} allows us to study the dynamics of the system at collapse and to determine the timescale on which experiments can be performed in the region of large negative a_{FB}. This region is relevant for applications such as molecule formation and boson-induced superfluidity [6].

For the experiment we employ a ^{40}K-^{87}Rb mixture, which is produced using techniques already presented in detail elsewhere [11, 14]. We prepare samples of typically 10^5 K fermions and 5×10^5 Rb bosons at about 1μK in a magnetic trap. The mixture is then transferred to an optical trap created by two off-resonance laser beams, at a wavelength of 1030 nm, crossing in the horizontal plane. The trap depth for both species is about 5 μK, and the trap frequencies $\omega/2\pi$ are (120,92,126) Hz for Rb and a factor about $\sqrt{(87/40)}$ larger for K. The atoms are prepared in their absolute ground state $|F = 9/2, m_F = -9/2\rangle$ for K and $|1, 1\rangle$ for Rb. A homogeneous magnetic field is then raised to $B\approx$550 G, in the vicinity of the broadest K-Rb Feshbach resonance for these states, shown in Fig. 1 [10, 11]. The samples are then further cooled by reducing the depth of the optical trap in 2.4 s and then recompressed to the full depth in 150 ms [15]. This allows to produce samples composed of up to 10^5 atoms per species, at $T < 0.2T_c$ for Rb and $T\approx0.3T_F$ for K, where T_c=230 nK and T_F=630 nK. The Bose gas is completely enclosed in the Fermi gas, whose dimensions are approximately twice the ones of the BEC. The Feshbach resonance we employ was so far studied only in thermal samples [10, 11], where its presence is signalled by an increase of three-body atom loss centered at B=546.7(4) G [16], as shown in Fig.1a. In a boson-fermion mixture three-body processes involving two bosons and one fermion are the dominant loss mechanism. They are predicted to depend on bosons and fermions density distributions n_B and n_F and on the interspecies scattering length as $\Gamma_3 = K_3 \int n_B^2 n_F d^3x$, where $K_3 \propto a_{FB}^4$ [17]. The maximum of the losses therefore indicates the position of the resonance center B_0. In addition to losses, we see also a heating of the system due to the density dependence of Γ_3 that favors the loss of the coldest atoms at the center of the distributions [18].

In order to have a precise control of the scattering length, it is necessary to gain information on all parameters that determine the resonance shape $a_{FB}(B) = a_{bg}(1-\Delta/(B-B_0))$. These are the background scattering length a_{bg}, the center B_0 and the width Δ. The former has been determined through Feshbach spectroscopy [11, 16] to be a_{bg}=-185(4) a_0 , and the expectation for the

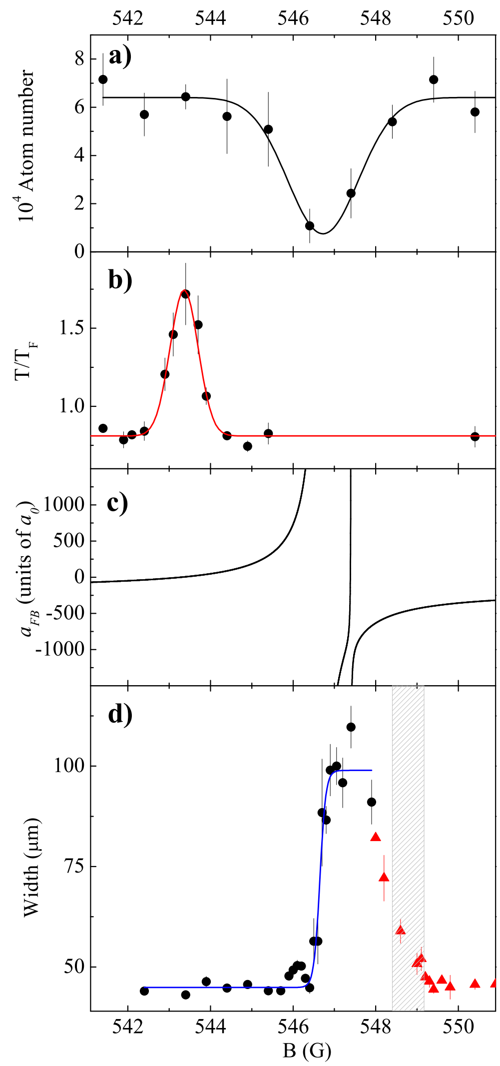

FIG. 1: (Color online) a) K atom number left in the trap after 50 ms hold time at a fixed magnetic field B in nondegenerate mixture (T=1.1 μK); b) efficiency of sympathetic cooling of fermions around the zero-crossing position; c) theoretical expectation for the fermion-boson scattering length a_{FB} at the Feshbach resonance; d) width of the Rb distribution after ballistic expansion from the trap. Here the degenerate mixture is prepared at B=543.4 G (circles) or B=551 G (triangles) and adiabatically brought to the final field B. The highlighted region marks the transition from a stable to an unstable regime.

width is $\Delta \approx$-3 G. This implies that in the vicinity of the resonance a_{FB} is positive only in a region extending from B_0 to about 3 G below, where a_{FB} crosses zero, as shown in Fig.1c. Determination of the boundaries between B-field regions with opposite signs of a_{FB} allows to determine experimentally the resonance parameters. In particular, we locate the zero-crossing position by studying the efficiency of sympathetic cooling of fermions during an evaporation at magnetic fields below the resonance. The efficiency is directly related to the interspecies thermalization rate, which in the vicinity of the zero-crossing varies as a_{FB}^2. As shown in Fig.1b, the temperature of the fermionic component at the end of the evaporation shows a marked increase centered at 543.4(2) G, which we identify as the a_{FB}=0 position.

The other physical property of the system that is directly related to a_{FB} is the interspecies interaction energy $U_{FB} = 2\pi\hbar^2 a_{FB}/\mu \int n_B n_F d^3x$, where μ is the reduced mass of the system. Each component is therefore felt by the other one as an attractive (repulsive) potential for negative (positive) a_{FB}. At a Feshbach resonance U_{FB} is large and it can substantially modify the distributions n_B, n_F. This can lead to phenomena such as collapse for $a_{FB} < 0$ or phase separation for $a_{FB} > 0$ [13], and will also affect the behavior of three-body losses. We expect the resonance center to be a sharp interface between these two opposite scenarios.

We have investigated these phenomena by adiabatically sweeping the magnetic field across the Feshbach resonance. In a first experiment the field is increased in 50 ms from B_i=543.4 G [19] to a final field B_f that is varied from 543.4 G to 548 G. We concentrate our attention on the bosonic component of the mixture, since it has a lower chemical potential, and is therefore more strongly affected by variations in U_{FB}. Fig.2 shows the typical profiles of the Bose gas after 10 ms of permanence at B_f and 18 ms of expansion from the optical trap at $B \approx$0 G [20]. We observe a decrease of the atom number as large as 80% when B_f approaches B_0, but the condensate surprisingly survives. This observation is in contrast with the expected heating associated to three-body atom losses, and is a strong indication that the repulsive interaction is driving the system into a regime of phase separation. The absence of heating indeed indicates that three-body losses remove preferentially the warmest atoms in the system, and therefore that the only overlap of the two clouds comes from their boundary regions, where the most energetic atoms reside. A mean-field model of our system [21] confirms that for the large positive a_{FB} expected for B close to B_0 the two components tend to phase separate into two vertically stacked domains, due to the anisotropy originated by gravity.

Once the field is tuned above B_0, the U_{FB} suddenly changes sign, and the two components tend to collapse at the center of the trap because such energy is larger than the local intraspecies repulsive energy [22, 23]. The sudden increase of the density overlap of the two components now promotes the loss of the coldest atoms at the trap center, with a resulting rapid heating of the system. We observe this collapse as B_f is tuned above 546.6 G, where the condensate disappears, and one is left with a thermal gas at $T \approx$600 nK. This study therefore indicates that the scattering length changes sign between 546.6 and 546.7 G. This value of B_0 is in good agreement with the value extracted from the loss feature in a thermal mixture. Fig.1d (circles) summarizes this behavior. In this

Figure we plot the vertical width of the Bose gas when fitted with a single gaussian profile. This shows the clear transition from the $a_{FB}>0$ regime at $B<B_0$ where the width stays approximately constant to the $a_{FB}<0$ regime where the condensate is destroyed by the collapse instability. The Fermi gas behaves in a similar way, featuring a sudden increase of the temperature when the field is tuned above B_0. A phenomenological fit of the experimental data with a Boltzmann growth function indicates B_0=546.65(20) G.

Note that the width of the Bose gas shown in Fig.1d features a small local maximum around 546 G, where a_{FB} is of the order of 1000 a_0, that we interpret as an increased confinement felt by the bosons in the trap due to the repulsion by the fermions. The width drops again in the vicinity of the resonance because of the reduction in the atom numbers. Further investigation of this regime of large positive a_{FB} is in progress. Fig.1c shows also a very narrow spin resonance predicted by our quantum collisional model [11]. We actually detect it in the experiment as an increase in the loss and heating rate in a magnetic field range of 100 mG centered at 547.4(1) G.

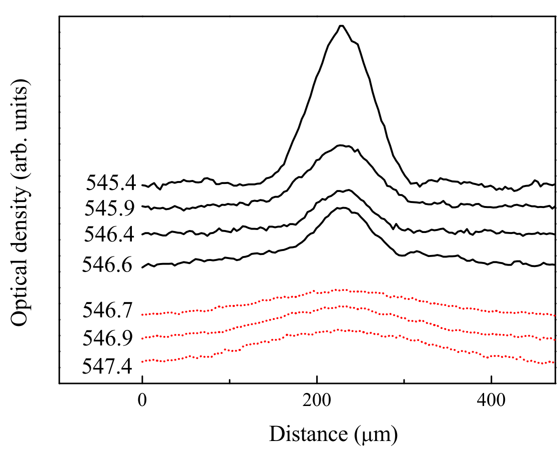

FIG. 2: (Color online) Profiles of the Bose gas in the mixture for various final values of the magnetic field ramp starting at B=543.4 G. The condensate survives despite the large atom losses as long as $B<B_0$ (continous lines). For $B>B_0$ the condensate is destroyed by collapse (dotted lines).

The dynamics of collapse can now be studied in detail, thanks to the possibility of tuning of a_{FB} to arbitrarily large values in times as short as a few 100 μs. Fig.3 shows the time-evolution of a mixture that was prepared at $B_i\approx$551 G, where $a\approx$-300 a_0, and then rapidly brought to B_f=547.5 G where we expect a scattering length a_{FB}=-700^{-600}_{-800} a_0 that is too large for the system to be stable. We observe a rapid loss of about 2/3 of the atoms in both components in the first 5-6 ms, while both the width and the center of the bosonic momentum distribution start to oscillate at frequencies of the order of the bare trap frequency. The oscillations are the evidence of the presence of a large attractive interaction energy U_{FB}, which modifies the effective trap potential experienced by the bosons. The mutual attraction tends to increase the overlap of the two components and therefore also increases the rate of three-body losses beyond the a_{FB}^4 dependence. After 6 ms most of the atoms in the center of the two clouds are lost and the condensate is almost totally heated into a thermal sample. The subsequent decrease of density leads to a rapid decrease of Γ_3, almost stopping the atom losses.

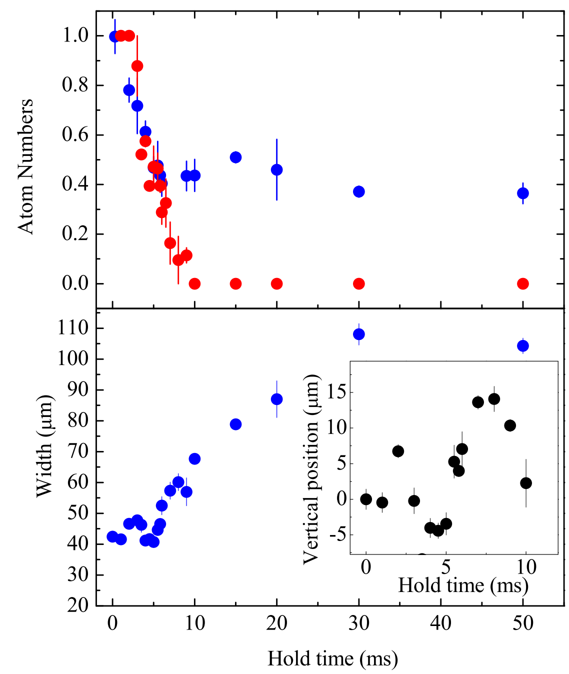

FIG. 3: (Color online) a) Evolution of the atom number in the bosonic component(circles) and in the fermionic component (triangles) after a rapid change of the magnetic field from B_f=551 G to B_f=547.5 G. b) Evolution of the width and vertical position (inset) of the bosonic component.

We have observed this rapid loss of atoms followed by a much slower decay and a heating of the system associated to collapse for magnetic fields up to B=548.6 G, while for fields larger than B=549.4 G the mixture is clearly stable. In the intermediate region the system shows a moderate loss of atoms and shape excitations, presumably due to the sudden variation of the interaction energy. This behavior is summarized by the measurement reported in Fig.1d (triangles). Here we have prepared the mixture at B_i=551 G, swept the field in 50 ms to a variable B_f on the negative-a_{FB} side of the resonance, and then waited for additional 20 ms. The width of the condensate starts to increase around B_f=549.4 G until around B_f=548.6 G the condensate is totally heated into a thermal sample as a consequence of collapse. The transition region between stable and unstable conditions is highlighted. The corresponding scattering length range is a_{FB}=-600÷-350 a_0

in qualitative accordance with the prediction of a static mean field model [21] of a critical scattering length a_c=-400 a_0 for the nominal atom numbers N_B=N_F=4×10^4 in this specific experiment.

It is important to note that the collapse does not apparently take place on timescales much smaller than the trap period, as it can be expected. For example, if the field is brought from B_i=551 G to B_f=547.5 G in less than 2 ms and then back to 551 G in the same time, no apparent atom loss or excitation of the condensate is observed.

The possibility of a resonant control of a_{FB} will allow to test various aspects of strongly interacting Fermi-Bose systems, such as the scaling law for a_c with the atom density [21], the dynamics of the expansion [24], and theoretical issues including the role of beyond-mean-field corrections [25] dynamical mean-field models [26] and finite-temperature effects [27].

In conclusion, we have studied the behavior of a ^{40}K-^{87}Rb Fermi-Bose mixture at an interspecies Feshbach resonance, whose magnetic-field position and width have been precisely determined by locating the critical values for the interspecies scattering length a_{FB}. Besides an accurate investigation of mean-field effects, this resonance can be employed for precisely tuning a_{FB} for a variety of applications. In particular, we are now investigating the possibility of associating pairs of atoms into molecules using magnetic field sweeps across the resonance from the $a_{FB} < 0$ side, in analogy with what performed in homonuclear systems [3]. Preliminary studies indicate that the system can survive sweeps from $B > B_0$ to $B < B_0$ as slow as 2 ms/G without collapsing, since the time spent in the region of large negative a_{FB} is too short. Interestingly, this ramp speed is still smaller than the minimum ramp speed needed in homonuclear systems [28] to achieve the optimal atom-molecule conversion with adiabatic sweeps. This indicates the feasibility of producing heteronuclear fermionic molecules in this mixture. Instabilities can be totally avoided by preparing the mixture in optical lattices [29, 30]. The tunable interspecies interaction will help develop new strategies for the production and control of atomic and molecular quantum gases in lattices.

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Related investigations have been reported by a group in Hamburg after completion of this work [31].

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